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technical Report

United States Army
Belvoir Research, Development & Engineering Center
Fort Belvoir, Virginia 22060-5606

Report 2460

Galvanic Corrosion Initiatives

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Report Date: December 1987

88 1 21 016

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704 0188
Exp Date Jun 30, 1986

1a REPORT SECURITY CLASSIFICATION
Unclassified

1b RESTRICTIVE MARKINGS

2a SECURITY CLASSIFICATION AUTHORITY

2b DECLASSIFICATION / DOWNGRADING SCHEDULE

3 DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4 PERFORMING ORGANIZATION REPORT NUMBER(S)
2460

5 MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
Materials, Fuels & Lubricants
Belvoir RD&E Center

6b. OFFICE SYMBOL *(If applicable)*
STRBE-VC

7a NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
Fort Belvoir, VA 22060-5606

7b ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO

11. TITLE *(Include Security Classification)*

GALVANIC CORROSION INITIATIVES (Unclassified)

12. PERSONAL AUTHOR(S)
Dario A. Emeric, Lisa R. Whiting, Mark Burns

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM 01/85 TO 10/87

14. DATE OF REPORT *(Year, Month, Day)*
December 1987

15. PAGE COUNT
30

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
corrosion; acid rain; mechanical properties; composites; aluminum alloys; steels; bridges

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

In the past, there have been a number of material failures in Army equipment. Many of these failures were caused by galvanic corrosion. This research was performed to determine the effect of galvanic reactions on the mechanical properties of high strength materials in aggressive environments. Aluminum alloys, steels, and a graphite-epoxy composite were exposed to various environments, then tested to indicate whether the galvanic corrosion which developed was cosmetic or if it had an effect on the mechanical properties of the material. By doing this, the number of failures in military equipment could be reduced.

(Keywords)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
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22b TELEPHONE *(Include Area Code)*
703/664-1127

22c OFFICE SYMBOL
STRBE-VC

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

PREFACE

In the past, there have been numerous cases of material failures in the Army's bridges, primarily caused by some form of corrosion. One type of corrosion involved is **galvanic** corrosion, occurring when two dissimilar metals come in contact in an electrolyte. The electrolyte could be a marine or even a humid environment. When this contact occurs, the less noble metal (anode) corrodes in order to protect the more noble metal (cathode). By exposing galvanic couples of bridging materials in aggressive environments, the number of failures in bridges and other military equipment can be reduced.

The objective of research presented in this report was to determine the effect of galvanic reactions on the mechanical properties of high strength bridging materials in aggressive environments. Galvanic couples were made from various materials under consideration for Army bridges. These couples were exposed to aggressive environments and then corrosion rates and mechanical properties of each material were determined. The resulting data distinguished the developed corrosion as either being cosmetic or having an effect on the mechanical properties of the material.

This technical report presents testing descriptions, observations, and conclusions on 14 different materials having 44 combinations.

TABLE OF CONTENTS

SECTION I. TEST DESCRIPTION

This section presents listings of American Society for Testing and Materials (ASTM) standards and equipment used, the procedure followed, and the types of environment selected.

ASTM STANDARDS

ASTM proposed standard Gxx, *Test Method for Galvanic Corrosion in the Atmosphere*

ASTM D2344, *Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method*

ASTM E8, *Tension Testing of Metallic Materials*

ASTM G1, *Preparing, Cleaning, and Evaluating Corrosion Test Specimens*

ASTM G31, *Laboratory Immersion Corrosion Testing of Metals*

ASTM G44, *Alternate Immersion Stress Corrosion Testing in 3.5% Sodium Chloride Solution*

ASTM G82, *Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance*

EQUIPMENT USED

Harshaw Salt Spray Cabinet, Model #22, Harshaw Chemical Company

Tensilkut, Floor Model, Sieburg International, Incorporated

Immersion Bath, fabricated by Blair, Incorporated

Baldwin Tensile Tester, Model #472470, Southwark Division, Tate-Emery Company

Extensometer, Model #P3M, Satec, Incorporated

Hygrothermograph, Model #8368-50, Cole-Parmer

Scanning Electron Microscope, Model #1200B, AMRAY Company

Energy Dispersive Spectrum, Model #System 4, Princeton Gamma Tech

Scales, Model #B3000D, Ohaus

Calipers, Model #120, Starrett Company

Saw, Model Abrasimet, Buehler Limited

Cut off Wheel, Model Isocut, Buehler Limited

PROCEDURE

The galvanic testing was performed on materials considered for use in bridges being currently developed. Fourteen different materials were tested (Figure 1), resulting in 44 combinations (Figures 2 and 3). The following procedure was adapted from ASTM proposed standard Gxx, *Test Method for Galvanic Corrosion in the Atmosphere.*

Aluminum Alloys

- 2024-T3
- 5052-H32
- 6061-T6
- 7075-T6
- 7075-T73

High Strength Steels

- T-1
- AR-235

Carbon Steels

- AISI C1117 Cadmium Plated Steel
- 4140 Black Chrome Plated Steel
- 4340

Other Metals

- 360 Brass, comp. 22
- CRES AISI Type 430

Composites

- Graphite-Epoxy Composite
- Graphite-Epoxy Composite coated with Fiberglass

Figure 1. Materials for Galvanic Testing

	6061-T6	AISI C1117 cad pl	4140 blk chr pl	Brass	5052-H32	7075-T6	7075-T73	4340 Steel	CRES AISI 430	2024-T3
6061-T6	6061-T6 6061-T6	6061-T6 C1117	6061-T6 4140	6061-T6 Brass	6061-T6 7075-H32	6061-T6 7075-T6	6061-T6 7075-T73	6061-T6 4340	6061-T6 430	6061-T6 2024-T3
AISI C1117 cad pl	C1117 6061-T6	C1117 C1117								
4140 blk chr pl	4140 6061-T6		4140 4140							
Brass	Brass 6061-T6			Brass Brass						
5052-H32	5052-H32 6061-T6				5052-H32 5052-H32					
7075-T6	7075-T6 6061-T6					7075-T6 7075-T6	7075-T6 7075-T73			
7075-T73	7075-T73 6061-T6					7075-T73 7075-T6	7075-T73 7075-T73			
4340 Steel	4340 6061-T6							4340 4340		
CRES AISI 430	430 6061-T6								430 430	
2024-T3	2024-T3 6061-T6									2024-T3 2024-T3

Controls:

6061-T6/6061-T6
AISI C1117 cad pl/AISI C1117 cad pl
4140 blk chr pl/4140 blk chr pl
Brass/Brass
5052-H32/5052-H32
7075-T6/7075-T6
7075-T73/7075-T73
4340 Steel/4340 Steel
CRES AISI 430/CRES AISI 430
2024-T3/2024-T3

NOTE: cad pl — cadmium plated
blk chr pl — black chrome plated

Figure 2. Light Assault Bridge Test Matrix—30 Combinations

	AR-235	Graphite-Epoxy	Graphite-Epoxy with Fiberglass	T-1
AR-235	AR-235 AR-235	AR-235 graphite-epoxy	AR-235 graphite-epoxy	AR-235 T-1
Graphite-Epoxy	graphite-epoxy AR-235	graphite-epoxy graphite-epoxy	—	graphite-epoxy T-1
Graphite-Epoxy with Fiberglass	graphite-epoxy with fiberglass AR-235	graphite-epoxy with fiberglass graphite-epoxy	—	graphite-epoxy with fiberglass T-1
T-1	T-1 AR-235	T-1 graphite-epoxy	T-1 graphite-epoxy with fiberglass	T-1 T-1

NOTE: All samples in triplicate for each test.

Controls:

AR-235/AR-235
graphite-epoxy/graphite-epoxy
T-1/T-1
astralloy/astraalloy
graphite-epoxy/fiberglass/graphite-epoxy

Figure 3. Heavy Assault Bridge Test Matrix—14 Combinations

1. A 4" x 6" panel of one material is degreased and weighed.

2. This panel is then sandwiched between two 1" x 3" panels of another material. These two panels are also degreased and weighed (Figure 4). The samples are wet assembled using MIL-S-81733 polysulfide-based sealant to avoid any galvanic reaction between the stainless steel bolts and the panels.

3. Three samples of each combination are then placed in the test environment for a given length of time.

4. After environmental testing of the panels is completed, the panels are photographed and disassembled. The panels were then rephotographed to show the area where galvanic corrosion occurred.

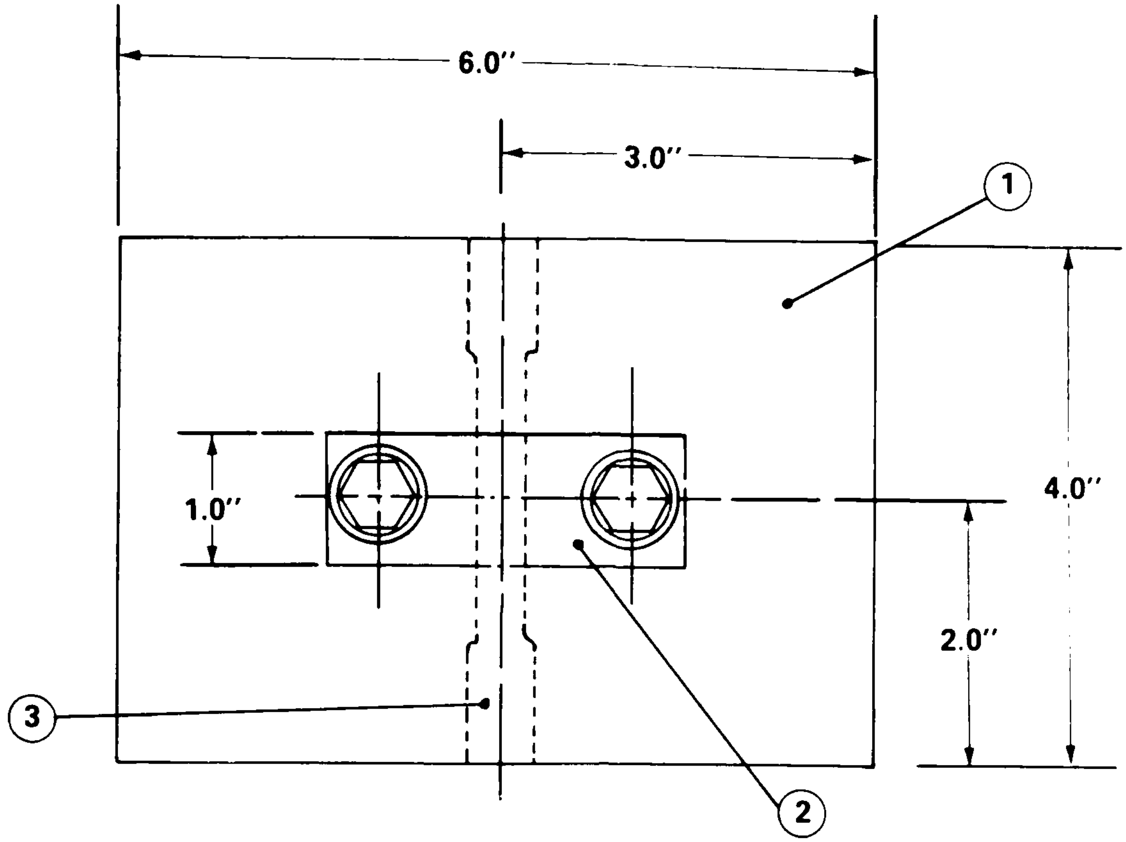
5. The panels are chemically cleaned according to ASTM G1, *Preparing, Cleaning and Evaluating Corrosion Test Specimens*, and then reweighed. The corrosion rate of each panel is found using the following equation:

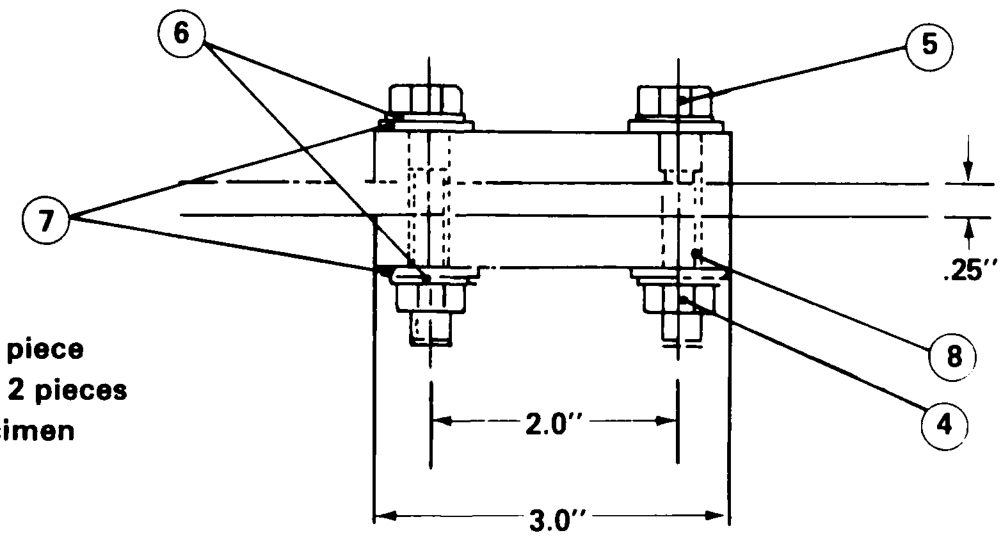
Corrosion Rate = (KxW)/(AxTxD), where
K = constant (3.45 x 10^6 for mpy)
T = time of exposure (hours)
A = area (cm^2)
W = mass loss (g)
D = density (g/cm^3)

6. Any change in the mechanical properties is then determined. A subsize ¼" wide tensile sample with a 1" gage length is cut out of the center of the large panel (Figure 4) and tested according to ASTM E8, *Tension Testing of Metallic Materials*. The properties measured are ultimate strength, yield strength, and percent elongation.

7. These properties are compared to the baseline to determine any deviations caused by the galvanic reaction between the materials in the given environment.

8. In the case of the graphite-epoxy composites, the tensile tests were not performed due to the difficulty in keeping fiberglass tabs glued to the ends of the composite tensile bars as recommended by ASTM. None of the epoxies available had a high enough shear strength to keep the tabs on the sample during testing. Therefore, the test was changed to ASTM D2344, an interlaminar shear test, as an indication of any changes in physical properties. Samples were cut 1.5" x .25" x .25" and had a 1" span. A three-point load was applied to bend and break the sample.





KEY:

1. anodic panel - 1 piece
2. cathodic panel - 2 pieces
3. tensile test specimen
4. nut - 2 pieces
5. bolt - 2 pieces
6. washers - 4 pieces
7. insulating washers - 4 pieces
8. insulating sleeve - 2 pieces

Figure 4. Specimen for Galvanic Corrosion Testing

ENVIRONMENTS

The environments for this experiment were chosen to recreate the actual conditions these materials may be exposed to when used in military equipment. The test environments included the following.

Immersion Bath

In this test the panels were exposed to a 3.5% Sodium Chloride (NaCl) solution, acidified to a pH of 4.1. This pH was chosen to simulate an acid rain environment. The 3.5% NaCl is the most corrosive marine solution. Panels were cycled in and out of this bath—10 minutes soaking and 50 minutes air drying. This continued for 75 days. Three different immersion bath tests were run, each at a different temperature—35 °F, 70 °F, and 125 °F.

Cyclic Accelerated Aggressive Environment

This test used the same solution as the immersion bath, 3.5% NaCl acidified to a pH of 4.1. The difference was that the panels were in a salt spray chamber, not immersed in the solution. They were cycled through different environments including:

24 hours in a cold box (< 32 °F)
4 hours thaw (room temperature)

then:

1 hour salt spray
2 hours purge/drying cycle
4 hours high humidity soak

The last three steps in the cycle were performed 20 times per week, then the panels were returned to the cold box. The complete test took 120 days.

Outdoor Exposure

The outdoor exposure took place behind our laboratory at Fort Belvoir, Virginia. The panels were placed on a rack at a 30 degree angle from the horizontal, facing south. The exposure period was 15 months. The amount and pH of the rain, and the temperature and humidity were monitored daily.

SECTION II. TEST OBSERVATIONS

Note: Galvanic couples are designated by (alloy/alloy). The first indicates the large panel on which the mechanical testing was done. The second alloy indicates the small panels coupled to it. All discussions center on the large panel.

35 °F IMMERSION BATH

The ultimate strength of some galvanic couples was affected by corrosion in cold temperature. The following couples showed a loss of ultimate strength greater than 10%:

360 Brass/360 Brass
360 Brass/6061-T6
2024-T3/2024-T3
2024-T3/6061-T6
7075-T73/6061-T6

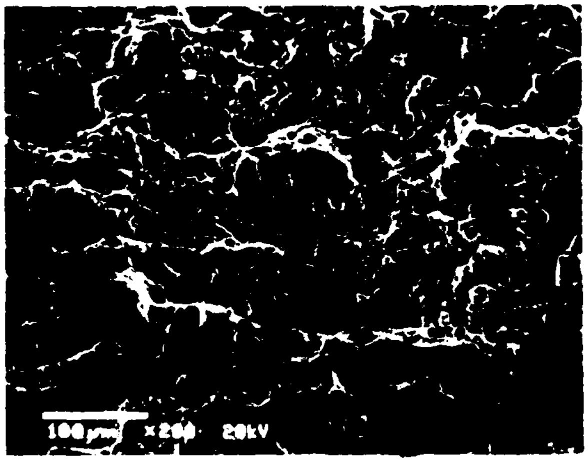
The couples containing the 360 Brass and 2024-T3 seemed to show a loss of strength dependent upon material and not the galvanic corrosion. When placed in the 35 °F immersion bath, the samples showed a loss of strength whether they were coupled with themselves or in a galvanic couple. This would seem to indicate that these materials do not perform well in the industrial marine environment at low temperature, even if used alone. The loss of ultimate strength of the last combination (7075-T73/6061-T6) appeared to be due to the galvanic interactions of the two materials. This loss of ultimate strength of 7075-T73 did not occur when the material was coupled with 7075-T6 or with itself at this temperature.

The 35 °F immersion bath showed no significant galvanic corrosion effect on the yield strength of any couples tested. None of the couples showed any loss of yield strength greater than 10%.

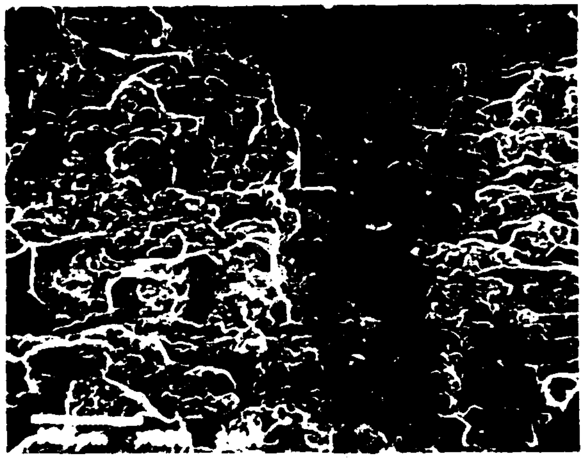
The elongation of many of the combinations was nevertheless affected by corrosion in the low temperature immersion bath. The combinations were:

360 Brass/360 Brass
2024-T3/2024-T3
5052-H32/5052-H32
5052-H32/6061-T6
7075-T6/6061/T6
7075-T6/7075-T73
430 Stainless Steel/6061-T6
6061-T6/430 Stainless Steel
6061-T6/360 Brass
T-1/AR-235

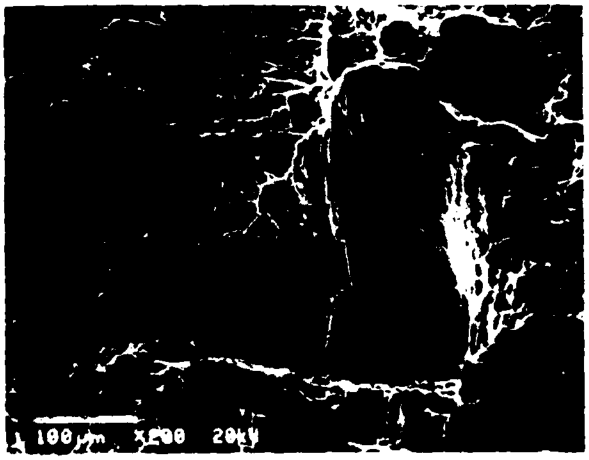
A loss of elongation indicated that the material was becoming more brittle. Both the 5052-H32 and 7075-T6 showed a loss of elongation, regardless of what they were coupled with. For these materials, the 35 °F temperature was a problem, mainly because it could have caused catastrophic failure rather than the galvanic corrosion. Scanning Electron Microscopy (SEM) showed a change in the fracture surface when the 7075-T6 was coupled with 6061-T6 and 7075-T73. The baseline fracture of 7075-T6 (Figure 5a) showed dimples indicating a ductile rupture along with some shear planes. The fracture surface of 7075-T6, when coupled to 6061-T6 at 35 °F, had more shear planes and fewer dimples (Figure 5b). This was even more pronounced in the 7075-T6 coupled with 7075-T73 fracture face (Figure 5c). Here, the shear planes were larger and closer together. These changes in the fracture surface confirmed the loss of ductility. The T-1, 6061-T6, and 430 Stainless Steel all had a loss of elongation because this temperature appeared to cause that galvanic couple to react. The 2024-T3 and 360 Brass on the other hand appeared to have a loss of elongation due to the galvanic corrosion effect upon the metal at that temperature. Coupling these materials with other metals such as 6061-T did reduce this effect; therefore, it may be possible to avoid the problem of brittleness at this temperature.



a Baseline



b After testing in the 35°F immersion bath coupled with 6061-T6



c After testing in the 35°F immersion bath coupled with 7075-T73

Figure 5. SEM Fracture Surfaces—7075-T6

70°F IMMERSION BATH

At 70°F, the effect that the acidic marine environment had on the galvanic couples was very different than its effect at 35°F. There was only one material that showed a decrease in its ultimate strength—6061-T6 of the 6061-T6/4340 steel combination. At room temperature the galvanic reaction between these two was accelerated. This was the only aluminum combination that had a loss of ultimate strength and yield strength.

The combinations that lost yield strength included:

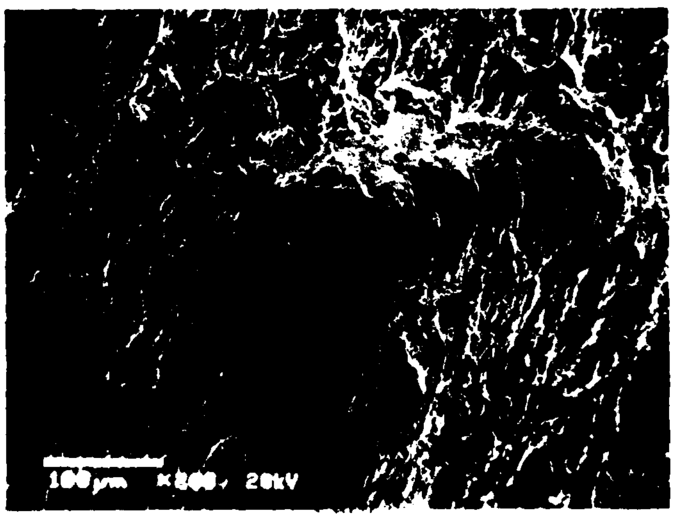
360 Brass/6061-T6
4340 Steel/6061-T6
T-1/T-1
T-1/AR-235
T-1/Composite
T-1/Composite-fiberglass

The first three listed lost their strength due to the galvanic reaction between the anode and the cathode. The photographs from the SEM indicated a change in the fracture surfaces when there was a loss in yield strength. The baseline fracture of 360 Brass (Figure 6a) showed microvoids over the entire surface. When 360 Brass was coupled with 6061-T6 in the 70°F immersion bath, the resulting fracture surface was quite different (Figure 6b). Most of the microvoids were elongated indicating shear stresses, and there were cleavage planes in the center of the fracture. The last four combinations showed a loss of strength because of the environment. T-1 did not appear to be a viable metal in an acidic marine environment, no matter what it was coupled with. All its combinations showed losses in strength greater than 10%.

There did not seem to be any correlation between the changes in ultimate strength and those of yield strength. This was true at all the temperatures studied. At 70°F, there seemed to be some coordination between the losses of yield strength and the losses in elongation. All combinations but one that decreased in yield strength showed a decrease in their percent elongation. This indicated that the sample was becoming more brittle and reaching its elastic limit sooner. The list of the samples that lost some elongation included:

6061-T6/4340 Steel
6061-T6/360 Brass
360 Brass/360 Brass
360 Brass/6061-T6
2024-T3/2024-T3
5052-H32/5052-H32
T-1/AR-235
T-1/T-1
T-1/Composite
T-1/Composite-fiberglass
C1117/C1117
C1117/6061-T6

a Baseline



b After testing in the 70°F immersion bath coupled with 6061-T6

Figure 6. SEM Fracture Surfaces—360 Brass

All but the last two on this list showed a decrease in the percent elongation. The last two combinations (C1117) increased their elongation when tested in this environment, which could be due to the natural aging of the material. This increase in elongation did not affect the yield or ultimate strength of the material.

125 °F IMMERSION BATH

The 125 °F immersion bath created another very different set of circumstances. At this temperature it is generally known that the oxygen content of the water is increased, which usually causes an increase in corrosion rate. The effect it has on the strength of the materials is not necessarily the same. As in the 70 °F bath, the ultimate strength of most materials was not affected. Only two of the combinations showed any losses:

6061-T6/4340 Steel
6061-T6/360 Brass

These are two pairs in which 6061-T6 was considered very anodic to the other metal. The galvanic reaction which causes pitting occurred in these combinations and affected the mechanical properties of the 6061-T6.

The yield strength of most of the combinations did not show as much change as would be expected. Only three of the combinations showed significant loss of yield strength:

6061-T6/4340 Steel
C1117/C1117
T-1/AR-235

Most couples did not lose any yield strength. This appeared to be directly related to the galvanic corrosion at high temperature. At higher temperatures, materials are usually more ductile, which keeps their yield strength stable, even when corrosion is occurring. Except for the first pair, which is highly reactive, there did not seem to be any correlation between ultimate strength and yield strength at this temperature.

The elongation of the following materials was affected at 125 °F:

6061-T6/430 Stainless Steel
6061-T6/4340 Steel
6061-T6/360 Brass
6061-T6/2024-T3
T-1/AR-235
T-1/Composite
AR-235/AR-235
AR-235/Composite
C1117/6061-T6

The 6061-T6 seemed to be very susceptible to losses of elongation when coupled with ferrous and brass alloys. The T-1 steel only suffered losses in elongation when coupled with another steel (AR-235) and with the composite. When the composite was coated with fiberglass, there did not appear to be any problem. This was also the case with the AR-235. It showed a loss of ductility with the composite but not when coated. The T-1 acted as the anode in the combinations containing T-1 and AR-235. It lost ductility when combined with the AR-235, but the AR-235 did not. The C1117/6061-T6 combination showed the same trend at 125 °F as it did at 70 °F. It increased its percent elongation. In this case, it only occurred with the galvanic pair, and not when the metal was coupled to itself. Overall, many combinations held up quite well when tested in the 125 °F immersion bath.

There was no effect on the shear strength of the composite at any of the three temperatures. Neither the composite nor the composite covered with fiberglass were affected by the galvanic reactions.

CORRELATIONS WITH CORROSION RATES

At 35 °F, the corrosion rates of the galvanic couples could usually be correlated with the information obtained on the mechanical properties. Of all the combinations that showed a loss of properties at 35 °F, all but two had a direct relation with the amount of corrosion the large panel obtained. The brass coupled with 6061-T6 had a lower corrosion rate than brass coupled with brass. This in turn meant that the brass maintained its mechanical properties better in the galvanic couple with aluminum. This was also true of 2024-T3/6061-T6. The reverse was true for the rest of the aluminum combinations. The 7075-T6/6061-T6, 7075-T6/7075-T73, 7075-T73/6061-T6, 7075-T73/7075-T6, 6061-T6/430 Stainless Steel, and 6061-T6/360 Brass all had higher corrosion rates than when coupled to themselves which caused a loss in the elongation of the panel, and in some cases a loss of ultimate and yield strength. Two materials did not follow this trend, 430 Stainless Steel and T-1 Steel. When 430 Stainless Steel was coupled with 6061-T6, it had a lower corrosion rate than its control, but still showed a loss of elongation compared to its control. The same was true when T-1 was coupled with AR-235. While it had a lower corrosion rate than T-1/T-1, it showed a significant loss in its elongation, and slight losses in strength. This indicated that the corrosion rates of these materials were not good indications of the mechanical integrity of these materials.

The situation was much less consistent at 70 °F. Only a few combinations followed the trends mentioned above. The 6061-T6/4340, 6061-T6/360 Brass, T-1/Composite, and T-1/Composite fiberglass had higher corrosion rates than 6061-T6/6061-T6 and T-1/T-1. The couples also showed losses in their strengths and elongation when compared to 6061-T6/6061-T6 and T-1/T-1. The opposite was true of 2024-T3/6061-T6 and when it was compared to its control.

The rest of the combinations did not follow these typical patterns. The 5052-H32/6061-T6 had a higher corrosion rate than 5052-H32/5052-H32, but also had slightly higher mechanical properties. This unexpected occurrence meant that the corrosion appearing on this combination did not affect the structural integrity of this material. The C1117/6061-T6 had almost the same corrosion rate as C1117/C1117. All the mechanical properties were approximately the same also. At this temperature (70 °F), the cadmium plating provided enough protection so there did not appear to be much effect from galvanic interaction on the steel. Both the 360 Brass/6061-T6 and the 4340/6061-T6 had lower corrosion rates than 360 Brass/360 Brass and 4340/4340. The mechanical properties of each reacted differently. In the case of 360 Brass/6061-T6, the ultimate strength and the elongation of the brass were higher than that of the 360 Brass/360 Brass, but the yield strength was lower. For the 4340/6061-T6, the ultimate strength and the yield strength were lower than that of 4340/4340, but the elongation was higher. There did not seem to be any correlation between the corrosion rates and the mechanical properties of these materials.

T-1 steel reacted differently when coupled to AR-235 than when coupled to composites at 70 °F. It had a lower corrosion rate than T-1/T-1. The ultimate and yield strengths were higher than the control, but the elongation was lower.

At 125 °F, the corrosion rates were usually higher than they were at the other temperatures. The only exceptions were 360 Brass, C1117, 430 Stainless Steel, and the composites. This did not consistently reduce the mechanical properties of the materials. The 6061-T6 followed a pattern when coupled with 360 Brass, 430 Stainless Steel, and 4340 Steel. All these combinations had a higher corrosion rate than the control 6061-T6, but lost ultimate strength, yield strength, and elongation at 125 °F. When 6061-T6 was combined with 2024-T3 it had the same corrosion rate as 6061-T6/6061-T6 as well as the same ultimate and yield strength. The only property showing a loss was the elongation. This was unusual because there was no change in the corrosion rate but the material became embrittled due to the galvanic reaction.

AR-235 had a higher corrosion rate when coupled with composite than it did when coupled with itself at 125 °F. This was the only difference in the couples. The mechanical properties of AR-235 were no different than the control. T-1 was not that consistent. When coupled with AR-235, it had a higher corrosion rate than T-1/T-1. The ultimate strength was also higher, but the yield strength and the elongation were lower than the control. T-1 followed a typical pattern when combined with composite. It had a lower corrosion rate than T-1/T-1, and all the mechanical properties were higher.

The C1117/6061-T6 combination did not follow any trend. It had a higher corrosion rate than the control (C1117/C1117), but there was no difference in the ultimate strength. The yield strength of C1117 when coupled with 6061-T6, was lower than the control as would be expected, but the elongation was higher. This again may be due to the aging effects.

COMPARISON BETWEEN TEMPERATURES

The immersion tests were done at three different temperatures in order to study the range of climate Army equipment may be subjected to. The three temperatures—35 °, 70 °, and 125 °F—caused the materials to act differently. The corrosion rates of the materials were the easiest to predict because many combinations showed an increase in corrosion of the large panel as the temperature increased. Most steels fell into this category, as well as some aluminum. The combinations included:

AR-235/AR-235
AR-235/Composite
AR-235/Composite-fiberglass
AR-235/T-1
T-1/T-1
T-1/Composite
T-1/Composite-fiberglass
T-1/AR-235
6061-T6/4340
5052-H32/5052-H32
4340/4340
7075-T6/7075-T6
7075-T73/7075-T6

A few combinations did not show any change in corrosion rate at the different temperatures. The two brass combinations, as well as the 430 Stainless Steel/430 Stainless Steel, were the only couples to do this. From a corrosion standpoint, these materials are best suited for the multi-climate environments that most equipment will be used in. The remaining combinations followed an unusual trend. The corrosion rate decreased from 35 °F to 70 °F, and then increased between 70 °F and 125 °F. This indicated that room temperature was the least corrosive environment for these combinations, not 35 °F. The couples in this category included:

6061-T-6/6061-T6
6061-T6/4140 Black Chrome
6061-T6/430 Stainless Steel
6061-T6/360 Brass
6061-T6/2024-T3
6061-T6/5052-H32
6061-T6/7075-T6
6061-T6/7075-T73
6061-T6/C1117
C1117/C1117
C1117/6061-T6
4140 Black Chrome/4140 Black Chrome
4140 Black Chrome/6061-T6
2024-T3/2024-T3
2024-T3/6061-T6

5052-H32/6061-T6
4340/6061-T6
7075-T6/6061-T6
7075-T73/7075-T73
7075-T73/6061-T6
7075-T6/7075-T73

The 430 Stainless Steel/6061-T6 was the only sample that did the opposite of this. It showed the highest rate of corrosion at room temperature, and the lowest at 125 °F.

The ultimate strength of these materials was the most stable property. Many of the couples showed no change in ultimate strength at the different temperatures. A few combinations had ultimate strengths that increased toward the baseline as the temperature increased. These couples were:

360 Brass/360 Brass
360 Brass/6061-T6
2024-T3/2024-T3
2024-T3/6061-T6 (increased from 35 °F to 70 °F, then leveled off)

There were also a few aluminum alloys that had an ultimate strength that decreased as the temperature increased. They were:

6061-T6/4340
6061-T6/360 Brass

The 7075-T73/6061-T6 showed an increase in ultimate strength at 70 °F and a decrease at 125 °F. This was not what was expected, but it correlated with the trend in the corrosion rate.

The yield strength of these combinations was affected quite differently by the test temperature than the ultimate strength. The yield strength of the following couples decreased as the temperature increased:

360 Brass/6061-T6
6061-T6/4340
T-1/AR-235

Some of the couples yielded strengths that decrease when the test temperature was increased to 70 °F, and then the strength increased when the test was at 125 °F. This happened to the following combinations:

4340/6061-T6
C1117/C1117
T-1/T-1
T-1/Composite
T-1/Composite-fiberglass

The yield strength and the ultimate strength of these materials did not always follow the same trends when placed in the same environment. This made it very difficult to predict how a material will react in different situations.

The elongation of these materials was probably more affected by the corrosion at different temperatures than the other two properties. A few of the couples became more ductile as the temperature increased. These included:

2024-T3/2024-T3
7075-T6/6061-T6
7075-T6/7075-T73
T-1/AR-235

The last three couples only increased from 35° to 70°F, then leveled off at 125°F. There were also some combinations that became more brittle as the temperature increased. They were:

T-1/T-1
AR-235/AR-235
AR-235/Composite
6061-T6/2024-T3

The T-1/T-1 became embrittled at 70°F then leveled off at 125°F. The other three were the opposite; they remained the same at 35°F and 70°F, then became embrittled at 125°F. The following couples showed elongations that increased at 70°F and then decreased at 125°F:

430 Stainless Steel/6061-T6
6061-T6/4340
C1117/6061-T6
5052-H32/6061-T6

Then there were others that did the opposite. Their elongation decreased at 70°F and increased again at 125°F. These included:

6061-T6/360 Brass
T-1/Composite
T-1/Composite-fiberglass
360 Brass/360 Brass
360 Brass/6061-T6

These combinations are not recommended for use in equipment experiencing a wide variety of climates. The chance of catastrophic failure is greater in a material that becomes embrittled, especially with an increase in temperature of the acidified NaCl solution. This is not typical behavior.

Overall, the temperature of the environment of any material plays an important role in the behavior of its mechanical properties. This is especially true when there are galvanic reactions involved. Materials involved in a galvanic couple do not always follow the expected pattern of behavior.

IMMERSION BATH VS. OUTDOOR EXPOSURE TESTS

The outdoor exposure tests done at Fort Belvoir provided very different results compared to the immersion baths. Many couples experienced corrosion rates that were negligible, with rates of less than or equal to 0.04 mils per year (mpy). This includes the composites, brass, stainless steel, and aluminum coupled with any of the small panels. Even the steels that had corrosion rates greater than 0.04 mpy almost always had lower rates than those of the immersion baths. The only couples that did not fall into this category were C1117/C1117 and C1117/6061-T6. The C1117/C1117 had corrosion rates for both the large and small panels that were less than those in the 35 °F immersion bath, greater than those in the 70 °F immersion bath, and approximately the same as those in the 125 °F immersion bath. The small panels (6061-T6) of the C1117/6061-T6 in the outdoor exposure had corrosion rates that were less than all the immersion bath tests. The large panel (C1117) had a corrosion rate less than C1117 in the 35 °F immersion bath, but greater than both 70 °F and 125 °F immersion baths.

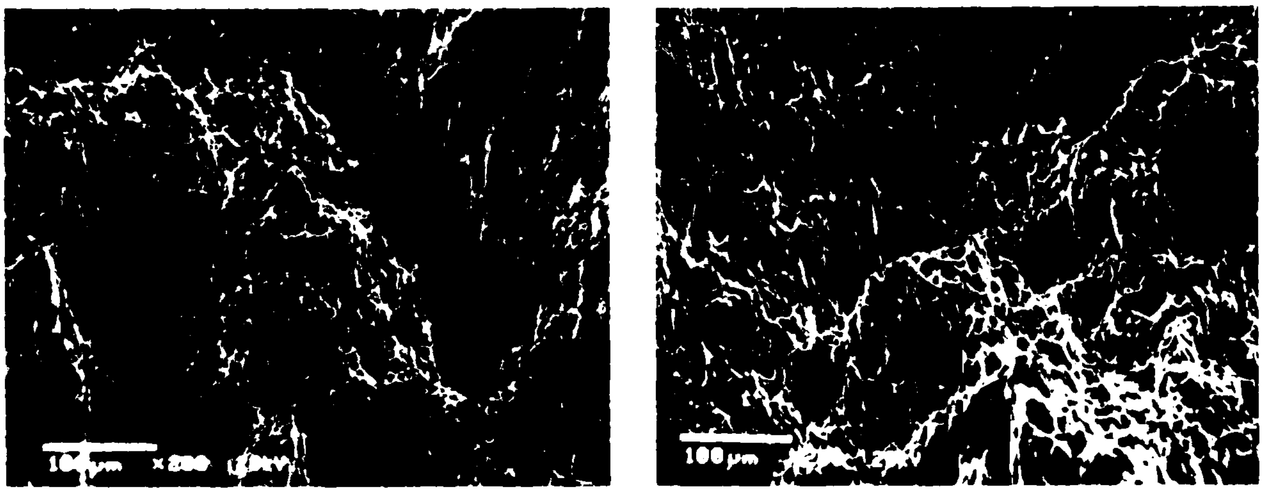
Another unusual aspect of these panels occurred when steels were coupled with aluminum. The aluminum should have acted as the anode, therefore protecting the steel. The 4340, 4140 Black Chrome, and C1117 did not show this. They all had higher corrosion rates when coupled to the 6061-T6 than when they were coupled with the same steel. This was different from most of the laboratory tests.

The difference in the behavior and the lower corrosion rates was due to the absence of NaCl during the outdoor exposure. Even though the pH of the outdoor tests resembled those of the immersion tests, the outdoor test was in a mild industrial atmosphere. The test was not done in an area where NaCl is abundant. The NaCl not only increased the corrosion rates, but appeared to also be the main factor in any losses in mechanical properties during the immersion baths. When aluminum was in this mild industrial environment, it passivated so there was an aluminum oxide coating protecting the surface. This coating made the aluminum more noble, therefore causing the material it was combined with to corrode instead. When the aluminum is in a chloride environment, it does not passivate and that was why its corrosion rates were higher and the metals that were coupled to it were protected.

The mechanical properties of the outdoor exposure combinations did not show much variation from the baseline. None of the combinations had any loss of ultimate strength. Yield strength was affected only in the brass combinations. Both 360 Brass/360 Brass and 360 Brass/6061-T6 had losses in yield strength greater than 10%. The elongation of some couples did not decrease after the outdoor exposure test. The following combinations had losses in elongation greater than or equal to 10%:

360 Brass/6061-T6
4140 Black Chrome/4140 Black Chrome
2024-T3/2024-T3
2024-T3/6061-T6
5052-H32/5052-H32
5053-H32/6061-T6
6061-T6/6061-T6
6061-T6/5052-H32
6061-T6/7075-T73
6061-T6/C1117

Most of these combinations were not the ones that showed losses in the immersion baths. The 6061-T6 had a stable percent elongation in the chloride environment, but this was not the case for the outdoor exposure. The aluminum, especially 6061-T6 and 5052-H32 were susceptible to embrittlement in a mild industrial environment due to corrosion. The fracture surfaces of 6061-T6 baseline and outdoor exposure were quite similar (Figures 7a and 7b). Both primarily consisted of dimples that were between 5 and 10 microns in size. The edges had shear lips with elongated dimples. Although the elongation of 6061-T6 did decrease after the outdoor exposure, the effect could not be noticed on the fracture surfaces.



a Baseline

b After testing at outdoor exposure coupled with 5052-H32

Figure 7. SEM Fracture Surfaces—6061-T6

IMMERSION BATH VS CYCLIC ACCELERATED AGGRESSIVE ENVIRONMENT

The cyclic accelerated aggressive environment was a longer accelerated laboratory test than the immersion bath. The effect it had on the corrosion rates of the materials was usually less harsh than that of the immersion bath. The 125 °F immersion bath produced higher corrosion rates for all combinations except 2024-T3/2024-T3, 2024-T3/6061-T6 and 4140 Black Chrome/6061-T6. The 70 °F immersion bath had higher corrosion rates (large panel) for most of the combinations, but the following had higher rates for the cyclic accelerated aggressive environment:

- 6061-T6/6061-T6
- 6061-T6/360 Brass
- C1117/C1117
- C1117/6061-T6
- 4140 Black Chrome/4140 Black Chrome
- 4140 Black Chrome/6061-T6
- 2024-T3/2024-T3
- 2024-T3/6061-T6
- 5052-H32/6061-T6
- 4340/6061-T6
- 7075-T6/7075-T6
- 7075-T6/6061-T6
- 7075-T73/7075-T73
- 7075-T73/7075-T6
- 7075-T6/7075-T73

The 35 °F immersion bath had higher corrosion rates than all but a few of the cyclic accelerated aggressive environment tests. These included:

- 4140 Black Chrome/6061-T6
- 2024-T3/2024-T3
- 2024-T3/6061-T6
- 5052-H32/6061-T6
- 4340/6061-T6
- 7075-T6/7075-T6
- 7075-T6/7075-T73
- AR-235/Composite-fiberglass
- T-1/Composite

The most unusual occurrence of these cyclic accelerated aggressive environment test was that the galvanic reaction did not always happen the same as it did in the immersion baths. In the case of 4340 Steel, the steel was protected by the 6061-T6 aluminum in the immersion baths. This was not true for the cyclic accelerated aggressive environment. The steel corroded faster when it was combined with aluminum. The same was also true for 4140 Black Chrome. Overall, the corrosion rates of the cyclic accelerated aggressive environment most closely resembled those of the 70 °F immersion bath.

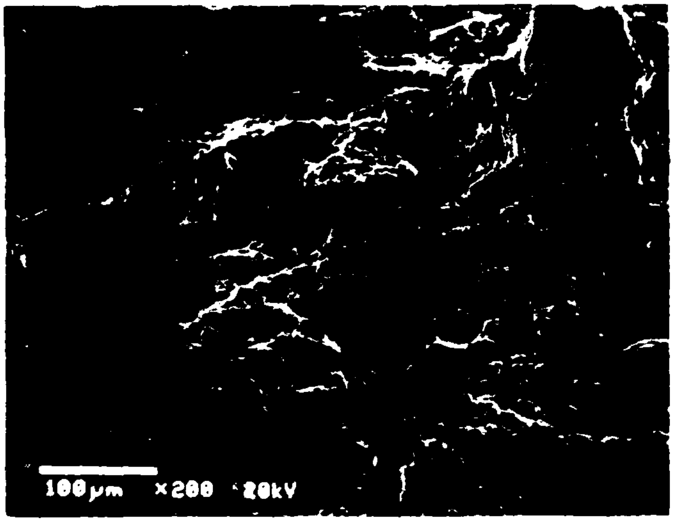
The mechanical properties of the cyclic accelerated aggressive environment combinations showed less deviation from the baseline than any of the immersion bath samples. Only one combination, 2024-T3/2024-T3 had a loss of ultimate strength greater than 10%. None of the couples showed a loss in yield strength. A few of the combinations did lose their elongation. These included:

6061-T6/360 Brass
6061-T6/4340
5052-H32/6061-T6
5052-H32/5052-H32
2024-T3/2024-T3
7075-T6/7075-T73
7075-T73/7075-T6
T-1/Composite

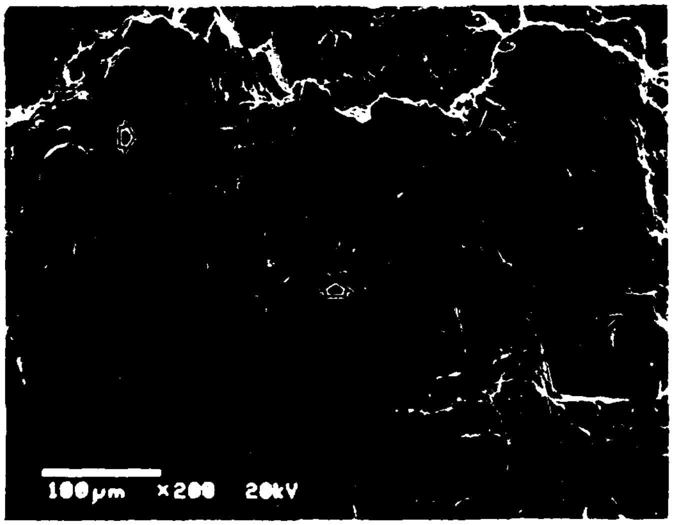
Most of these couples had less embrittlement than the immersion bath samples. The only material that did considerably worse in the cyclic accelerated aggressive environment was 2024-T3. Both of the combinations containing 2024-T3 behaved very poorly, and had almost no capacity for elongation after exposure. According to the fracture surface seen on the SEM, the 2024-T3 coupled with 6061-T6 appeared much more brittle than its baseline (Figures 8a and 8b). The baseline mostly consisted of small dimples. There were also a few brittle inclusions. The exposed sample had many brittle inclusions and flattened elongated areas. The dimples were larger than those of the baseline, which also indicated loss of ductility. The C1117 couples both showed an increase in elongation. This was similar to the 70°F and 125°F immersion tests.

The shear strength of the composite coupled with composite decreased in the cyclic accelerated aggressive environment. This decrease did not occur in the immersion baths, therefore it may be connected to the cycling between hot and cold temperatures. The loss of shear strength did not happen when the composite was coupled with either of the steels. This was possibly due to the protection of the composite by the anodic steels.

Overall, this cyclic test produced milder corrosion rates, as well as smaller losses in mechanical properties, than did the immersion baths. The only exception was the composite. It was this test that showed the problems that could arise when using composite materials in aggressive environments.



a Baseline



b After testing in the cyclic accelerated aggressive environment coupled with 6061-T6

Figure 8. SEM Fracture Surfaces—2024-T3

SECTION III. TEST CONCLUSIONS

This research studied the galvanic reactions of high strength materials in aggressive environments. Due to the adverse effect on the mechanical properties when some of the materials were combined, they should not be used in harsh environments. The temperature of the acidified 3.5% NaCl solution had a significant effect on the ductility of the metals that were galvanically coupled. The aluminum 6061-T6 was very susceptible to galvanic corrosion at 125 °F, and T-1 did not do well at 70 °F. Many of the aluminums showed a decrease in elongation after exposure at 35 °F.

Other combinations can be used if the materials are well insulated from one another. Very few problems were observed with the 4140 Steel that was black chrome plated, or the C1117 steel that was cadmium plated. The graphite-epoxy composite would be a good material in combination with steel if the composite could be plated with a material that would insulate it from the steel. Unfortunately, this type of composite is usually meant to be used uncoated which causes some problems. While the composite is anodically protected by steel and does not suffer losses in shear strength, the same is not true of the steel. Generally, it was determined that the composites: a) increase the corrosion rates of T-1 and AR-235 at 70 °F and in the cyclic accelerated aggressive environment, and b) decrease the percent elongation of the T-1 at 70 °F and in the cyclic acclerated aggressive environment. This test also showed the problems that could arise when using composite materials in aggressive environments.

Overall, it is not recommended that these materials be used in Army equipment without being insulated from the other metals that they come in contact with. In many cases the corrosion that occurs is not just cosmetic, but instead has an effect on the mechanical properties of the material. While a galvanic couple may be safe in one environment, it is detrimental in another. Therefore, because Army equipment—such as the heavy and light assault bridges—will be used and stored in a variety of environments, material compatibility in all environments must be considered in the design stages.

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